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A LABORATORY INVESTIGATION OF THE INFLUENCE EXERTED BY TAMPING-FOOT DIAMETER ON THE COMPACTED DENSITY OF A COHESIVE SOIL

A THESIS

Presented to

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By

John Guy Jackson, Jr.

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A LABORATORY INVESTIGATION OF THE INFLUENCE
EXERTED BY TAMPING-FOOT DIAMETER ON THE
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SUMMARY

Observations based on extensive performance testing of field compaction equipment in both Great Britain and the United States indicated that, for tamping rollers, there probably are optimum values of foot area and pressure that will give maximum soil compaction. The efficiency of this type of equipment is measured in terms of its ability to obtain a desired degree of compaction or density in the least number of passes.

This investigation was undertaken to determine the influence of foot size on the efficiency of soil compaction. To do this, laboratory dynamic compaction tests were performed with compaction hammer feet of two, three, four, and five inch diameters. The soil used was a red-brown, micaceous, fine, sandy, clayey silt of medium compressibility.

For each foot size a series of compactions was performed at varied water contents by an amount of work that was held constant. A large (one-sixth cubic foot) compaction mold was designed to minimize confining effects of the mold and their affect on the results obtained with the larger diameter feet. A compaction hammer weighing ten pounds and

having a free-fall of eighteen inches was constructed; the base of the hammer consists of a threaded socket into which the various compaction feet were attached. The data collected was used to compare the compacted densities produced by the various size feet.

This investigation led to the following conclusions: The density obtained from dynamic compaction is dependent upon the area or diameter of the compacting foot. For a given soil, moisture content, and method of dynamic compaction, there is a particular foot diameter which will produce the most efficient compaction. The effect of the size of the compaction foot on dry density is largest when the moisture content is near the optimum. At high values of moisture content which approach a saturated condition, the size of the compacting foot has no effect on density. The optimum moisture content produced by dynamic compaction at like amounts of work is independent of the area of the compacting foot. The optimum foot diameter decreases as the compactive effort increases. The most efficient compaction operation would be one in which the foot diameter was reduced at successive stages of the compaction process.

CHAPTER I

INTRODUCTION

The Federal-aid Highway Act of 1956 created the greatest public works program in history and provided for an expenditure of approximately twenty-seven and one-half billion dollars over a thirteen year period. Although the work under this program includes forty-one thousand miles of trunk-line highways, it covers only 1.2 per cent of the nation's total roads and streets mileage.(1) The past two decades have seen large-scale movements from rural to urban areas and a phenomenal rise in the number of automobiles and trucks choking congested traffic arteries. This situation has been and is now creating a pressing demand for expanding building and improvement programs for streets, urban expressways, by-pass routes, and arterial connections. To insure completion of a maximum improvement program, it is of prime importance that the roads be constructed to the best practicable standards for minimum future maintenance costs, and that initial construction be conducted as economically as possible.

One of the primary purposes of a road is to enable traffic to proceed with comfort; therefore, the road surface must be free from irregularities, cracks and other defects which interfere with smooth travel of a vehicle and cause discomfort to the passengers and possible damage to the vehicle itself or to goods it is carrying. Many of the defects to which surfaces are subject are, directly or indirectly, attributed to the soil foundation on which the road is built. Further, such defects are often of a more serious character than those resulting merely from faults in the surfacing.(2) Because traffic volumes, speeds, and wheel loads are continually rising, subgrades, base courses, and embankments can no longer be loosely deposited or placed without quality control, but must be carefully designed and constructed for maximum strength and stability to meet both present and future requirements.

Compaction is almost universally recognized as the key to construction of proper road foundations. Generally, compaction may be defined as the process of densification of soil by load application, causing a decrease in voids due to change in relative position and distortion of soil grains.

The density of soil is measured in terms of the weight of dry soil contained in a cubic foot of wet soil. Several factors influence the value of density obtained by compaction, the more important being the moisture content of the soil; the nature of the soil, that is, its grain size distribution and its physical properties; and the nature, including both type and amount, of the compactive effort used.(3) At low moisture contents soil usually has a high strength and is stiff and difficult to compact, with the result that low densities and high air void contents are obtained. At higher moisture contents the strength is less, and it becomes easier to reduce the air voids and compact the soil. At still higher moisture contents a condition is reached at which the soil is sufficiently workable for the air voids to be reduced to a very small value. Any further increase in the moisture content results in a decrease in the dry density owing to the increase in the void volume occupied by the water. The optimum moisture content and the corresponding maximum dry density are functions of the amount of energy provided by the method of compaction used. In general, as the amount of compactive energy applied is increased, the maximum dry density increases and the optimum moisture decreases.(4) Typical dry density-moisture content curves for a soil compacted with different amounts of input energy are shown in Figure 1 on the following page.

The success, that is, the economy and ease of obtaining compaction depends in large measure on the methods and on the type and weight of equipment used for rolling. In spite of the record boom in highway construction, Engineering News-Record recently reported keen competition that is driving bids down; this condition coupled with steadily increasing construction equipment prices at a time when contractors are investing heavily in equipment makes it mandatory that maximum equipment utilization, flexibility, and construction efficiency be incorporated into these gigantic building programs.(5) The tamping foot roller is most generally used for soil compaction in the United States, although it is not effective in cohesionless sand or in rock fills.(6) It is the opinion of many engineers that no superior type of equipment has been developed.(7) This machine had its inception about fifty years ago in an attempt to imitate the action obtained by running a flock of sheep over a loose fill--hence the name sheepsfoot tamper. It consists of a cylindrical drum from which prongs of feet extend. The principle of operation is that, as the

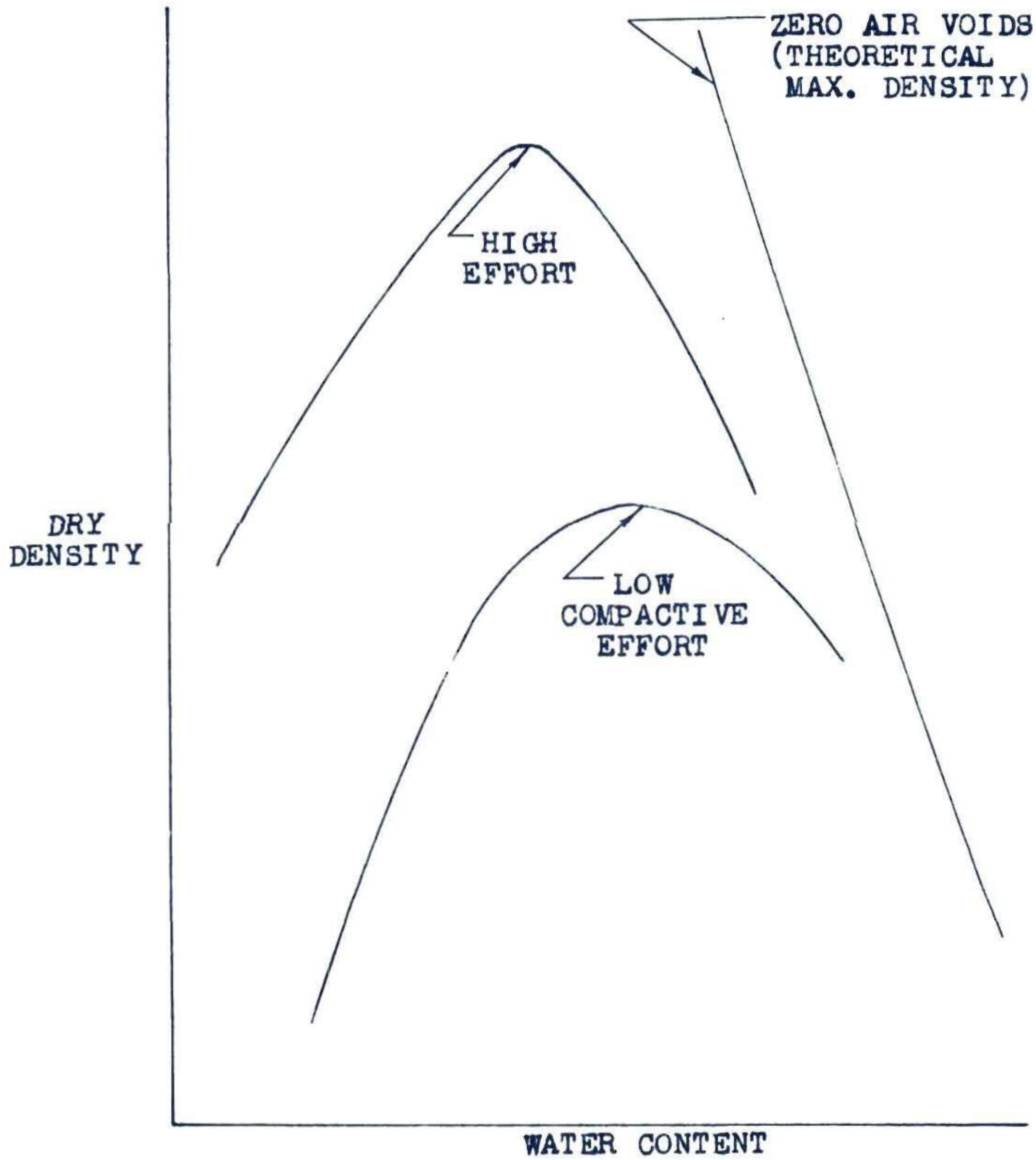


Fig. 1
TYPICAL MOISTURE-DENSITY CURVES FOR A SOIL
COMPACTED WITH DIFFERENT AMOUNTS OF EFFORT

drum is pulled forward, the feet penetrate the soil until bearing power sufficient for support is obtained. The compression of the soil directly under the feet together with the confining pressure of the adjacent soil helps to build up a dense layer at the bottom which increases in thickness until on the final rolling the feet ride on the soil surface. (8) The weight of the roller, the area and shape of the feet, and the spacing of the feet are variables in the sheepsfoot roller which influence compaction. Other variables include soil type, moisture content, initial density, and thickness of lift.

The existence of so many variables makes it difficult to present specific recommendations on the selection and use of that type of roller without many reservations(9); however, it is obvious that the tamping foot is the key to any investigation aimed at improving the efficiency of this piece of equipment. Efficiency, or to the contractor economy, is measured in terms of obtaining a desired degree of compaction with the least expenditure of energy, i.e. with rolling equipment, in the least number of passes. Synonymously, with a constant expenditure of energy in a particular soil, maximum efficiency is indicated by the maximum density obtained.

This study constitutes a laboratory investigation of the effect of the size of tamping foot on the dry density-moisture content relationship at constant expenditures of compactive energy.

CHAPTER II

PAST RESEARCH

A review was made of all available literature concerning compaction and included pertinent references contained in the Industrial Arts Index and Engineering Index from 1930 to date. A number of these references reported field observations and comparative performance results from tests using various types of compaction equipment; however, in the majority of cases, the variables affecting the results were so numerous that definite conclusions concerning the value of equipment modifications or improvements were impossible. Except for limited research reported from the Georgia Institute of Technology Soil Mechanics Laboratory, reports concerning laboratory investigations of compaction efficiency were almost non-existent.

R. R. Proctor, in a series of articles published in 1933 in Engineering News-Record concerning extensive compaction research by the Los Angeles Bureau of Water Works and Supply(10), observed that wide spacing of the feet on sheepsfoot rollers is preferable for efficient compaction. Proctor also was apparently the first to recommend increased roller weight for high density requirements.

The Highway Research Board in its 1938 Proceedings concluded that the number of trips necessary to obtain compaction with the sheepsfoot roller is contingent upon, among other things, the size and shape of feet, number of and spacing of tamping feet and the pressure exerted by the tamping feet. Today practically every State Highway Department in the nation has rigid specifications governing the use of sheepsfoot rollers. An example of these restrictions is the following excerpt from the California specifications:

> Tamping rollers shall consist of metal rollers, drums or shells, surmounted by metal studs with tamping feet projecting not less than 7 in. from the surface of the roller, drums or shell. Tamping feet shall be spaced not less than 6 in. nor more than 10 in. measured from center to center in any direction and the cross-sectional area of each tamping foot measured perpendicular to the axis of the stud shall not be less than 4 nor more than 12 sq.in.. The weight of tamping rollers shall be such that the load on each tamping foot shall not be less than 50 psi. of cross-sectional area. The load per tamper foot will be determined by dividing the total weight of the roller by the maximum number of tamper feet in one row parallel to, or approximately parallel to, the axis of the roller.(11)

Apparently the limits imposed have evolved through trial and error from contractor's or equipment manufacturer's field experience, since there appears to be no record until recently of any research aimed at developing specifications such as those given above.

Results of investigations conducted at the Road Research Laboratory in Britain suggested that for any given load there probably are optimum values of foot area and pressure that will give maximum soil compaction.(12) Further Research into the effects of varying the foot area and pressure for a number of different loads was recommended. Regardless of the actual weight of the sheepsfoot roller, the maximum unit pressure exerted by the feet on the soil cannot exceed a certain maximum value which is a function of the bearing capacity of the soil. If loads are applied which exceed the bearing capacity of the soil, the roller will sink into the soil until a sufficient number of teeth are in contact with the soil to reduce the maximum contact pressure to the bearing capacity of the soil for the existing condition. In some instances the roller will sink into the ground until even the drum is carrying a substantial load. Soon after the British observations, in an article reported on compaction research being conducted at the U. S. Army Corps of Engineers' Waterways Experiment Station, the authors observed that better compaction results might be obtained if, instead of reducing the total roller weight, the area of the feet were increased to the point where the bearing capacity of the soil was not exceeded.(13)

In following their previous conclusions, the Waterways Experiment Station began tests aimed at the selection of the allowable contact pressure and the proper size of feet for large rollers.(14) Model feet having end areas of six, nine, twelve, eighteen and twenty-four square inches were used and a load was applied through the hydraulic ram of a truck mounted drill rig and measured by means of a proving ring. The analysis indicates that for the soils tested there was a general relationship between the load penetration curves for the model feet and the observed behavior of sheepsfoot rollers. Rollers did not walk out during compaction in areas of penetration resistance less than the nominal computed pressures of the roller. In the three instances when the roller walked out, the load-penetration curves gave values greater than the nominal sheepsfoot pressures. The results imply that, so long as the contact pressure on the face of the sheepsfoot roller does not exceed the bearing capacity of the soil as determined by a load-penetration test, roller foot sizes could be increased considerably to permit application of tremendous roller weights. While these results are interesting, they do not provide any real evidence concerning roller efficiency as affected by the size of the tamping foot.

An attempt to investigate that relationship was made in conjunction with these tests when two sheepsfoot rollers with the same total weight were used to compact a soil. One roller had feet that were 8.25 square inches in size and the other had feet of 13.68 square inches. Both rollers achieved equivalent densities in compaction of the embankment; however, observations in the field indicated that neither roller was walking out during compaction even though the roller with larger feet was said to be easier to operate. Since both rollers apparently were exceeding the bearing capacity of the soil, no conclusions regarding foot size efficiencies can be drawn from the results.

In a subsequent report entitled "Effect of Size of Feet on Sheepsfoot Roller," the Waterways Experiment Station presented results of field compaction tests in which the compactive effort was varied by varying the size of tamping feet from seven to twenty-one square inches while maintaining a constant foot contact pressure and by varying the number of passes of the different foot sizes.(15) The most significant part of this report, insofar as this thesis is concerned, was its authors' conclusion that a more practical method of varying the contact pressure might be to use a roller with the maximum weight that is economical to tow and to vary the size of tamping feet. The authors suggest that this could be accomplished by designing sheepsfoot rollers with changeable feet; the proper foot size could be determined in the field for any given soil thereby resulting in the most efficient and economical compaction of any soil with a sheepsfoot roller.

Available data from carefully controlled field studies of rolling show moisture-density relationships almost identical with those developed from laboratory tests.(16) It is therefore entirely feasible that the proper size foot for a given soil and roller could be determined from laboratory tests, thereby circumventing the need for field determination. Only two significant laboratory studies involving compaction efficiency were found; both were unpublished M. S. theses from the Georgia Institute of Technology. Kennedy's investigation was undertaken to ascertain, by comparison of the densities and strengths of compacted soil samples, which of several different methods of compaction produced greatest efficiency and also to determine the factors influencing compaction efficiency and the reasons for their influence.(17) The investigation led to the conclusions that compaction by different methods at like amounts of work and water content does not necessarily produce equal amounts of compaction as expressed by dry density and that when total compactive energy, water content, layer thickness, and width of loaded area are held constant, the density and strength of a compacted soil are functions of the amount of energy applied per effort. The total energy change resulting from each pass of a sheepsfoot roller would be the same, however, regardless of the size of the tamping foot. This energy would of course be transmitted to the soil through the tamper foot and its size may definitely affect the manner in which this energy is dissipated.(18)

In his recommendations, Kennedy noted that the ratio of the diameter of the compacting foot or hammer to the thickness of the soil layer is a factor in soil compaction which could radically affect the design of compacting equipment.(19) This ratio was investigated the following year by J. G. Gulliver who found that at low ratios of foot diameter to soil layer thickness, where soil layers are thick with respect to the foot diameter, the largest feet produced the highest densities for given values of d/t.(20) For high ratios of d/t, the smallest feet produced the highest densities. This study definitely concluded that foot size affects the degree of compaction obtainable; however, further studies in which this variable is isolated from the effect of layer thickness and investigated under controlled energy conditions are necessary in order to discover its actual effect on compaction efficiency.

CHAPTER III

EQUIPMENT

The major items of equipment used in carrying out the experimental investigation described in this report are listed below. These include:

A. Compaction hammer.

Compactive effort was applied to the soil by a dynamic compaction device consisting of a ten pound hammer adjusted for an eighteen inch free fall. (See Figure 3). The device was constructed similar to the standard Marshall hammer, widely used in the testing of asphaltic concrete mixtures.(21)

B. Compaction feet.

Four circular steel feet, with diameters of two, three, four and five inches, were used to transmit the blows from the hammer to the soil. The feet were constructed with threaded spindles to permit attachment to the base of the compaction hammer. (See Figure 4).

C. Compaction mold.

The mold used was a large steel cylinder of ten and three-sixteenths inches internal diameter and a thickness of nine-sixteenths inches. The depth of the mold was three and seventeen thirty-seconds inches, which was predetermined to give a mold volume of one-sixth of a cubic foot. It was equipped with a detachable steel base plate and a collar which held the loose soil during compaction. (See Figure 5).

D. Soil.

The soil used throughout this investigation was a red-brown, micaceous, fine, sandy, clayey silt of medium compressibility. It was obtained from an embankment near the Georgia Institute of Technology Soil Mechanics Laboratory. The specific physical properties of the soil are listed below:

Specific Gravity of Solids	2.65
Liquid Limit	50
Plastic Limit	37
Plasticity Index	13
Grain Size Distribution	(See Appendix)
Revised Public Roads Classification	A-7
Airfield Classification System	ML
Standard Proctor Maximum Density	100.2
Optimum Moisture Content	22.0

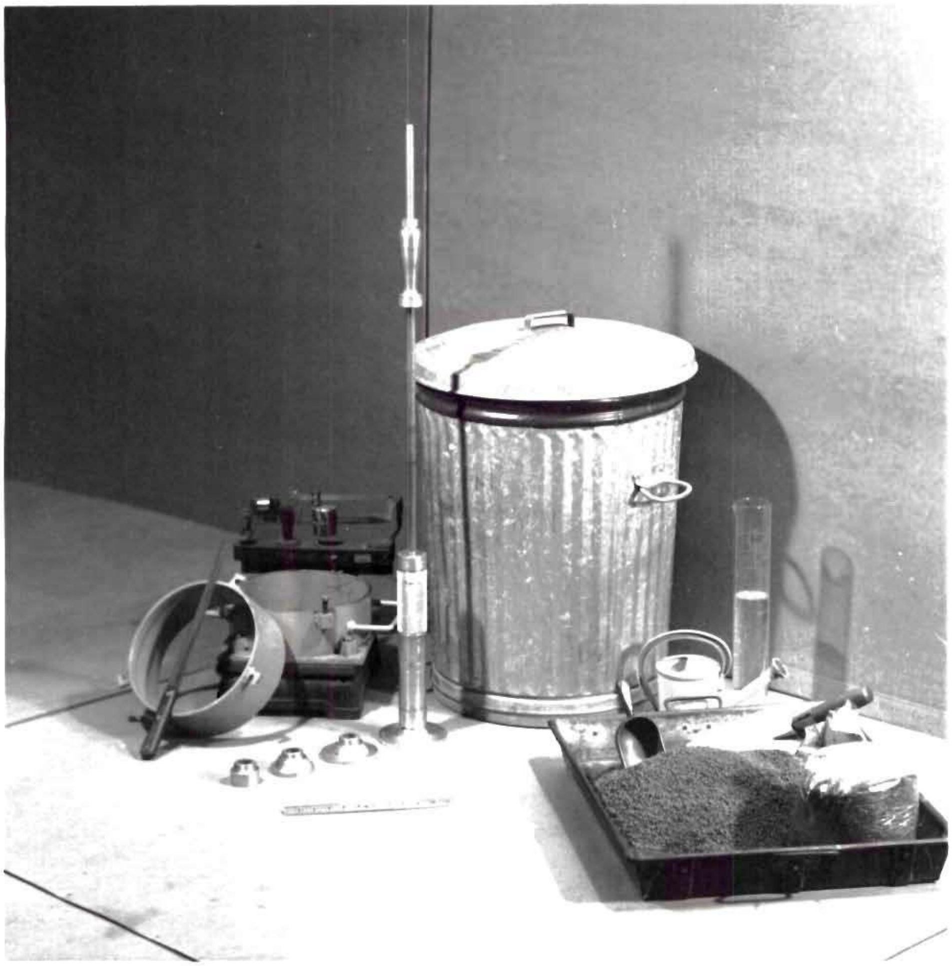


Fig. 2
LABORATORY COMPACTION EQUIPMENT
LEFT TO RIGHT: SAMPLE TRIMMING KNIFE, ONE-SIXTH CUBIC FOOT MOLD AND COLLAR, SEVENTY-FIVE POUND CAPACITY SCALE WITH ONE OUNCE SENSITIVITY, MARSHALL COMPACTION HAMMER WITH VARYING COMPACTION FEET, SOIL STORAGE CAN, SPRINKLING CAN AND GRADUATED CONTAINER FOR ADDING CALCULATED AMOUNTS OF WATER, MIXING PAN WITH SOIL SAMPLE, AND SAMPLE STORED IN MOISTURE PROOF POLYETHELENE BAG

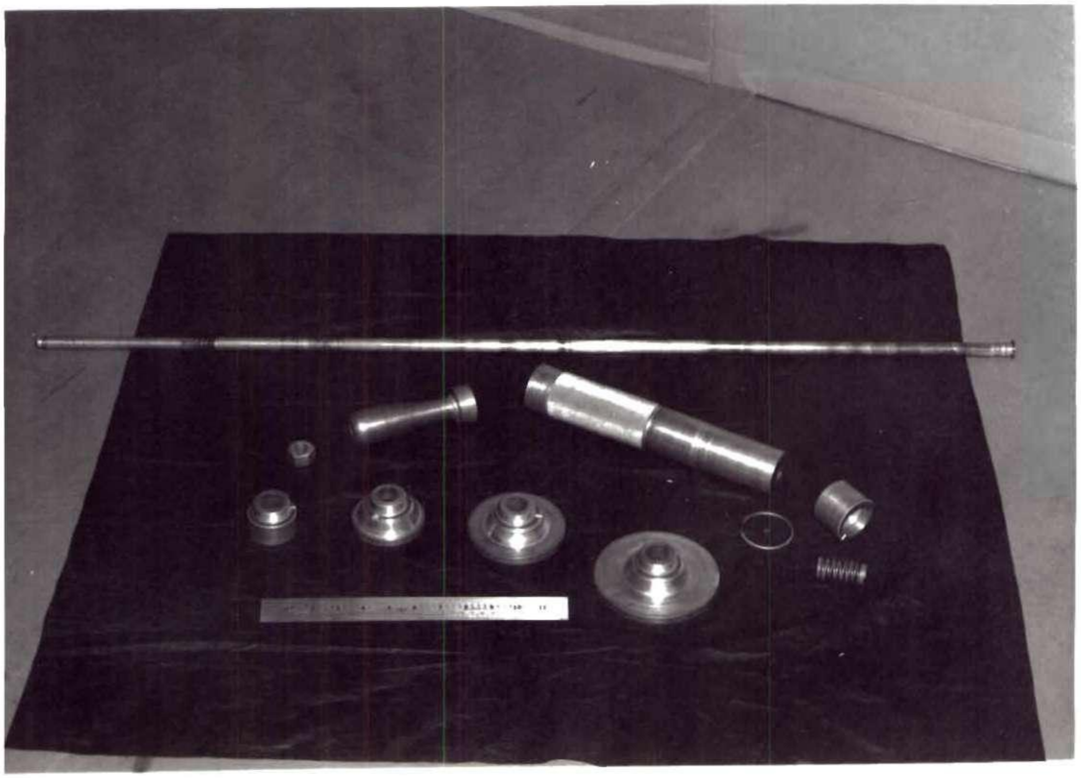
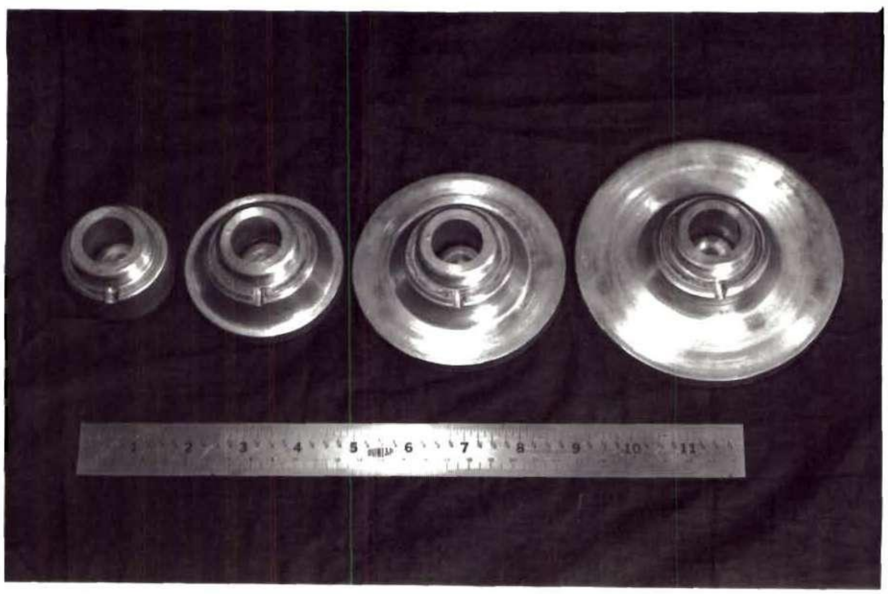


Fig. 3
DISASSEMBLED MARSHALL COMPACTION HAMMER

BOTTOM VIEW



TOP VIEW

Fig. 4
TWO, THREE, FOUR AND FIVE INCH DIAMETER
COMPACTION FEET FOR MARSHALL HAMMER

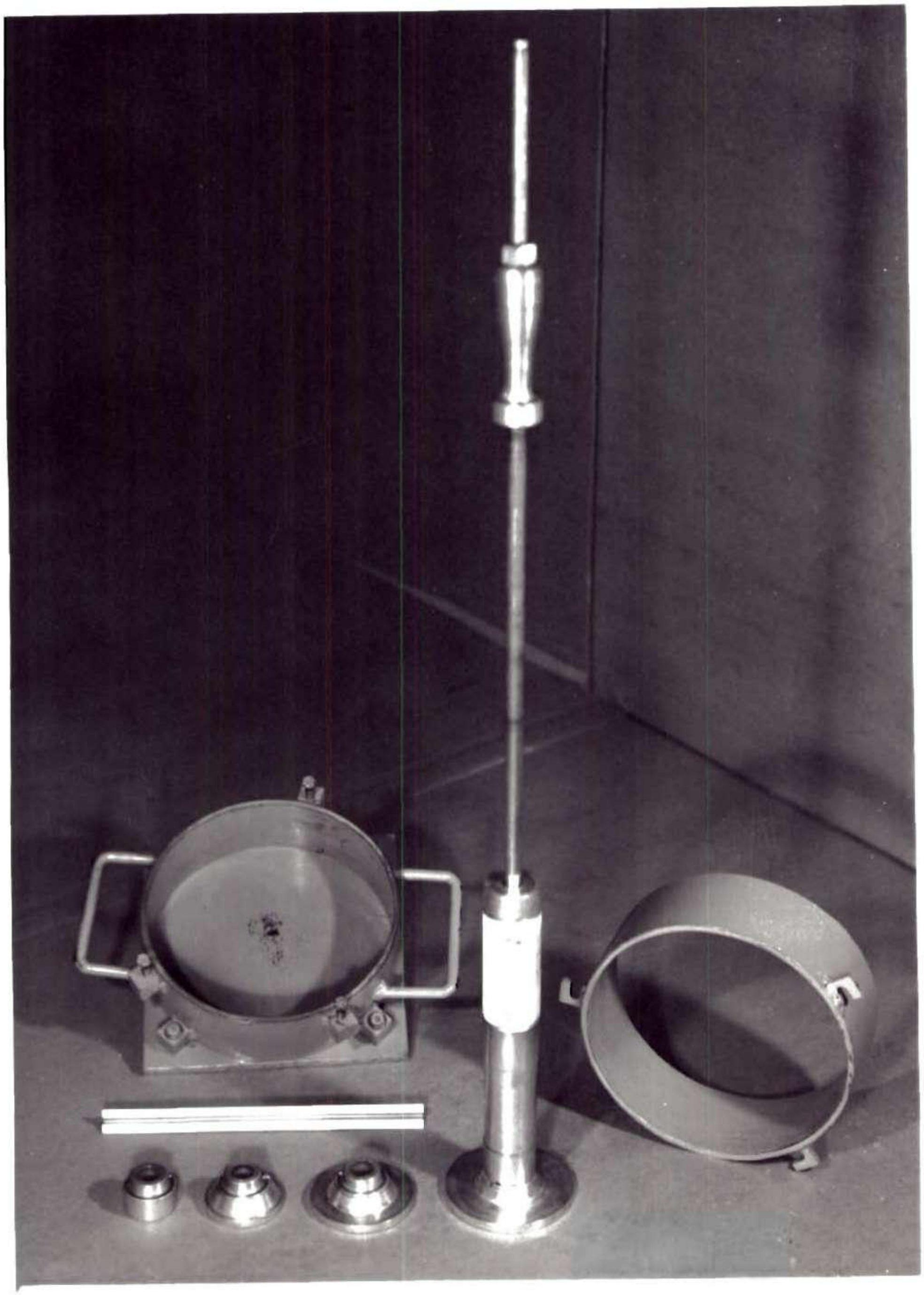


Fig. 5
ONE-SIXTH CUBIC FOOT COMPACTION MOLD AND COLLAR AND ASSEMBLED MARSHALL COMPACTION HAMMER WITH CHANGEABLE FEET

CHAPTER IV

PROCEDURE

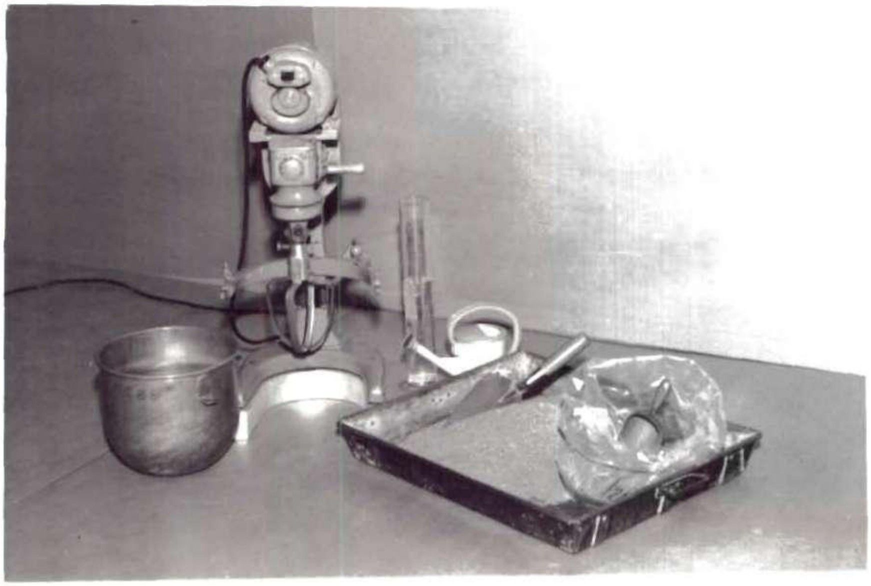
The test soil was brought indoors and force sieved through a U. S. Standard Number 4 Sieve (square 0.185 inch openings). The material retained on the screen was discarded while that passing was placed in large flat pans and allowed to air dry. It was then thoroughly mixed to insure uniformity and placed in covered containers.

Standard classification tests were performed on the soil. These included a specific gravity test to determine the specific gravity of soil solids (22), a grain size analysis to determine the grain size distribution of the soil (23), and the determination of liquid and plastic limits to indicate the effect of water content on the soil.(24) A standard Proctor test was carried out to determine the maximum density and optimum moisture content of the soil.(25)

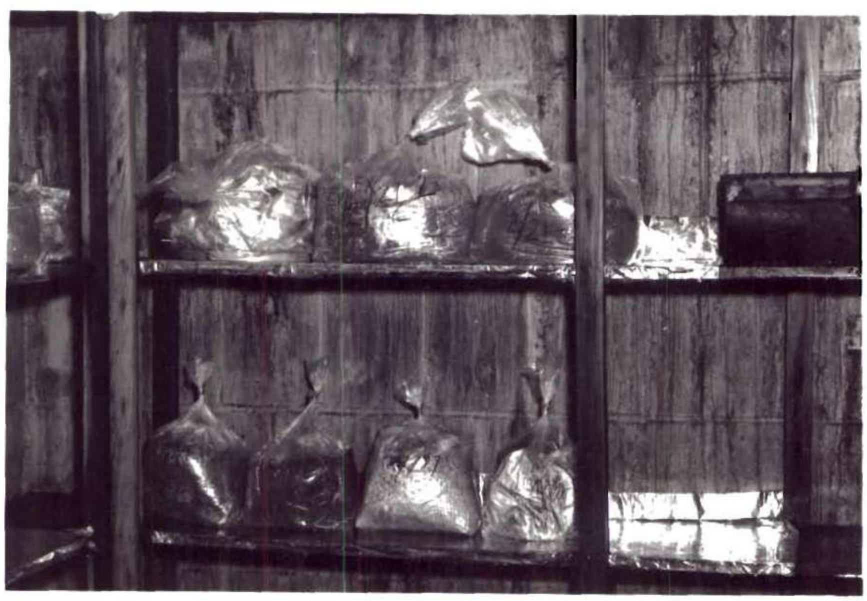
The water content of the test soil was determined daily for each of the closed containers. Trial compaction tests with the one-sixth cubic foot mold determined that a twenty-one pound sample was required for each test. This amount of soil, with equal parts by weight from each container, was prepared by adding the amount of water calculated to produce the desired moisture content in the compacted specimen and mixing it thoroughly with a large commercial food mixer. A water content determination was made of each specimen after preparation. The specimen was then sealed in double polyethelene bags, marked for identification, and stored overnight in a controlled moisture room to allow the water to become completely distributed and adsorbed by the soil. (See Figure 6).

There is a significant difference in the maximum density obtained by reusing the same soil throughout the compaction test and the density obtained by using fresh separate samples for each point on the moisture-density curve.(26) Since in actual construction work soil is compacted but once and at one water content, it is probable that the method using separate samples for each point would give results that are more representative of field conditions; therefore this procedure was followed during this investigation.

For each size compaction foot, samples were compacted containing water contents of fifteen, eighteen, twenty-one, twenty-four, and twenty-seven per cent. The principal compaction tests were conducted using the one-sixth cubic foot mold and a compactive effort of 12,420 foot-pounds per cubic foot; this is approximately the same energy expended in the



EQUIPMENT USED FOR MIXING AND BAGGING
CONTROLLED SOIL AND WATER SAMPLES



INTERIOR OF CONTROLLED MOISTURE ROOM
SHOWING SAMPLES STORED IN SEALED
DOUBLE POLYETHELENE BAGS

Fig. 6
MIXING AND STORING EQUIPMENT USED FOR WATER CONTENT CONTROL

standard Proctor compaction test. The work done on each dynamically compacted sample is the product of blows per layer, height of fall, weight of hammer, and number of layers. With the previously described test equipment, this effort required forty-six blows on each of three soil layers.

The sealed bag was opened and a moisture content determination made. About two inches of loose soil was placed in the mold and leveled with a small trowel. Compaction of the layer was then performed by the proper number of hammer blows evenly distributed over the soil surface. Since strength tests were not being performed on the compacted sample, scarifying of the compacted surface to insure bonding of subsequent layers was not necessary. Second and third layers of soil were compacted into the mold in like manner. Care was taken to insure that the mold was completely filled with compacted soil but only slightly overfilled, usually within one-quarter inch, so as not to jeopardize the compactive effort per constant volume concept. The soil surface was then planed off even with the top of the mold and the weight of the soil in the mold determined. This soil weight divided by the mold volume (one-sixth of a cubic foot) gave the wet density of the soil.

Two representative samples were cut from the specimen by driving a cutting cylinder through it and water content determinations were made. The dry density was then computed from the wet density and the water content of the compacted specimen. A sample data and computation sheet is contained in the appendix. (See Figure 13).

A set of samples, one for each foot size, was compacted at a single moisture content while using a compactive effort fifty per cent greater than that used in previous tests. This effort required sixty-nine blows per layer. In all other respects, however, the compaction procedure was the same.

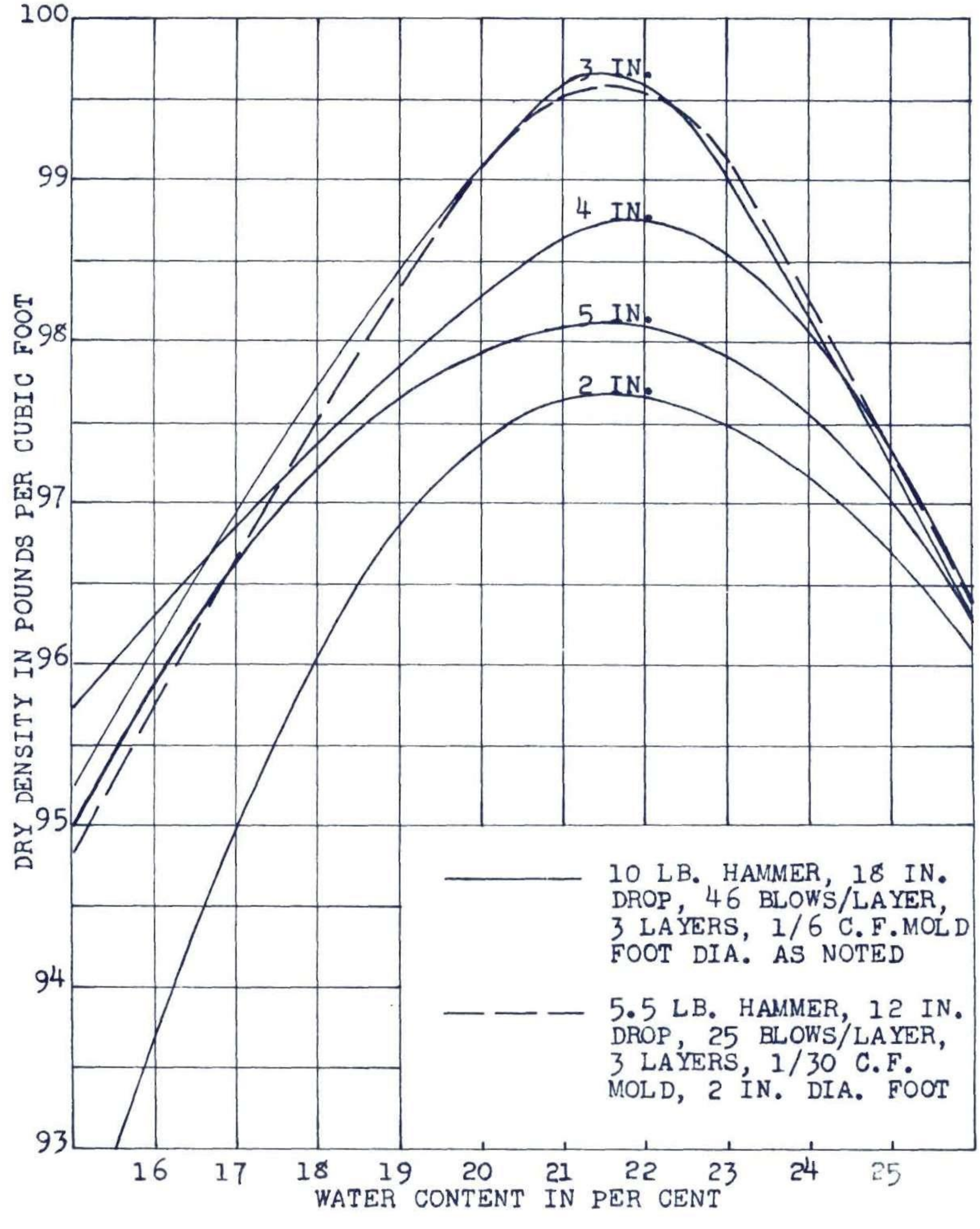


Fig. 7
EFFECT OF FOOT DIAMETER ON MOISTURE-DENSITY RELATIONSHIPS WITH A COMPACTIVE EFFORT OF 12,420 FOOT-POUNDS PER CUBIC FOOT

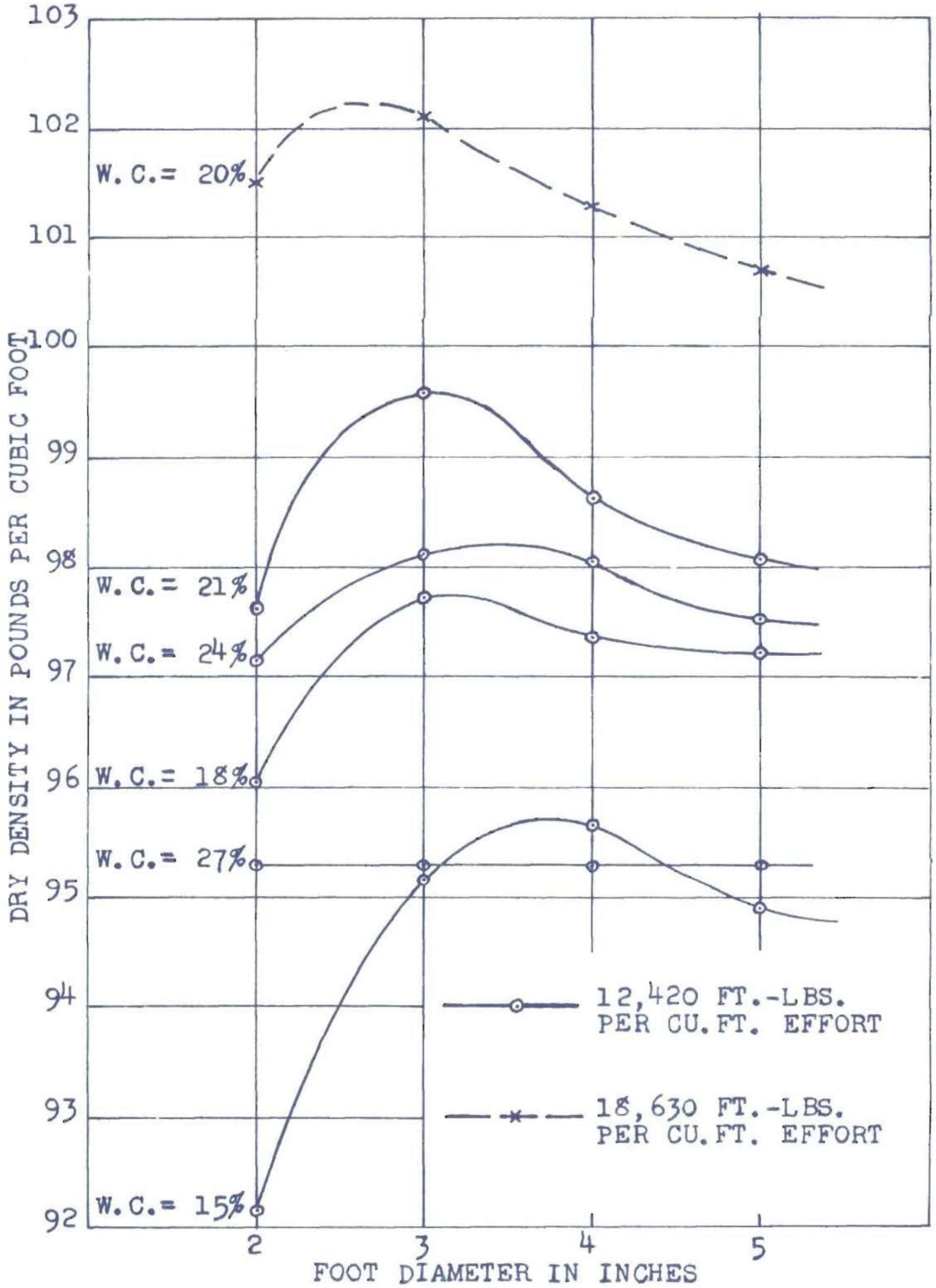


Fig. 8
DRY DENSITY-FOOT DIAMETER
RELATIONSHIPS AT VARIOUS WATER CONTENTS

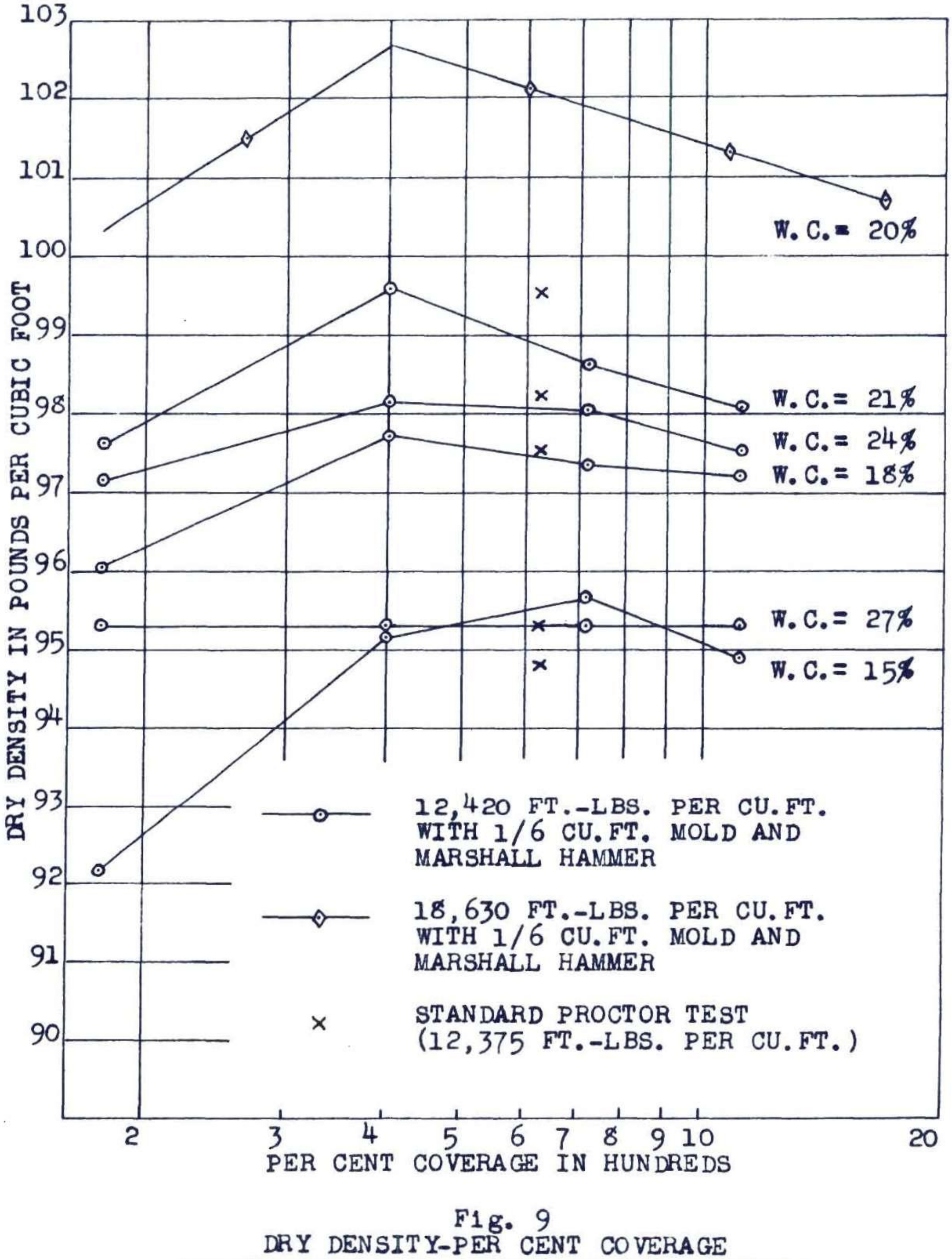
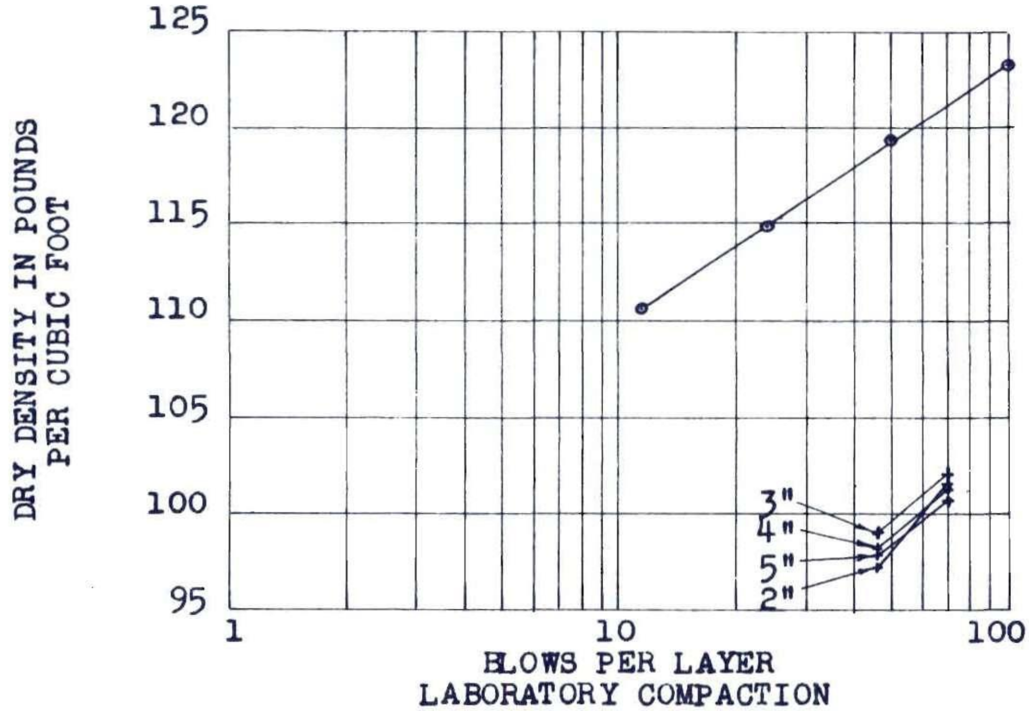
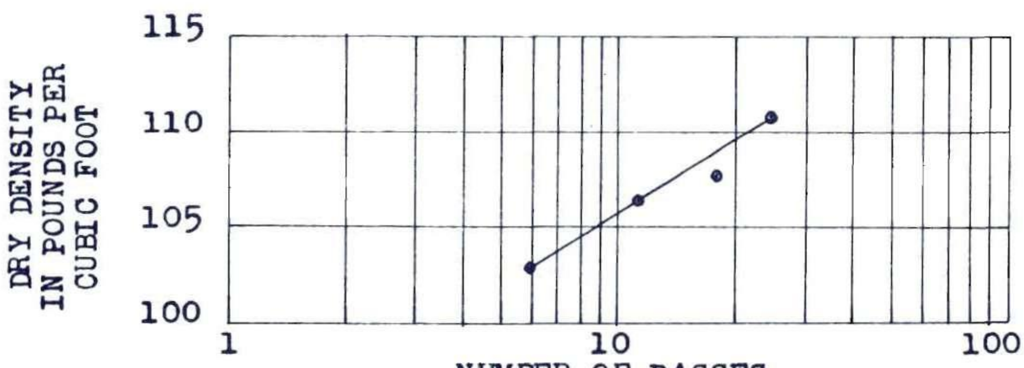


Fig. 9
DRY DENSITY-PER CENT COVERAGE
RELATIONSHIPS AT VARIOUS WATER CONTENTS





—⊙— DATA OBTAINED FROM "COMPACTION OF EMBANKMENTS, SUBGRADES, AND BASES," BULLETIN NO. 58, HIGHWAY RESEARCH BOARD, WASHINGTON, 1952, p. 26.

—×— 1/6 C.F. MOLD AND MARSHALL HAMMER AT 20% W.C.

Fig. 10
CORRELATION BETWEEN LABORATORY AND FIELD COMPACTION

CHAPTER V

DISCUSSION OF RESULTS

Analysis of the data began with plotting of conventional dry density versus water content curves. As previously stated, several factors influence the shape of the curves; they are the soil itself, its water content, and the compactive effort. The degree to which these factors, or variables, are controlled, therefore, directly affects the significance of the data.

Only one soil was used throughout these tests and especial care was taken to insure its homogeneity. A complete series of classification tests was run on each container of the prepared soil; the consistency of the results was excellent. Samples were made up with equal parts from each container and thoroughly mixed. A fresh sample of soil was used for each test since reusing previously compacted soil yields higher dry densities as a result of changes made in the soil structure by the previous compaction. (See Figure 18). This variable, therefore, was eliminated from the tests.

In field tests, the thickness of the layer of soil being compacted is an important consideration. However, in these laboratory tests, layers of equal thickness were compacted to the same final mold height to nullify any effect of this variable. In laboratory tests, the confining effects of the mold may definitely affect the test results. To obviate this factor a large diameter (ten and three-sixteenths inches) mold was used in conjunction with the wide range of compaction feet tested.

Although the water content of the soil was varied throughout the tests in order to study the moisture-density relationship, it was carefully controlled to allow comparisons at equal water contents. Samples were thoroughly mixed and stored an ample length of time to permit complete distribution of the moisture within the sample.

Of primary importance in this investigation is the compactive effort applied to the soil, including both the amount of effort and the manner in which it is applied. In order to study the effect of different size compaction feet, the amount of energy expended was kept constant; in the majority of the investigation 12,420 foot-pounds per cubic foot was applied, thus permitting comparison with the standard Proctor laboratory test. Total quantity of work was not a factor in this study.

British laboratory tests indicated that a constant amount of energy applied to a given soil produced identical moisture-density relationships.(27) Kennedy, on the other hand, found that the amount of work per application was an important factor affecting the degree of densification attained. (28) This variable was eliminated by using the same hammer and applying the total work with the same number of blows per layer throughout the tests. The weight of the component parts of the compacting device was not varied nor was the distance of free-fall of the hammer changed. Momentum and velocity of impact were therefore kept constant.

The only remaining factor about the compacting device which might influence the results attained was the size of the bearing plate through which the dynamic load application was transmitted. With the feet used in this investigation, a range of contact area from 3.14 to 19.63 square inches (2 inches to 5 inches diameter) was achieved. Dry density-moisture content curves obtained with a compactive effort of 12,420 foot-pounds per cubic foot are contained in Figure 7. It is obvious that the densities produced at like water contents are not identical. There are several rather striking observations that can be made from these curves.

While the maximum dry density obtained varied depending upon the diameter of the tamping foot, the optimum moisture content remained the same. This is considered an important discovery and indicates that should it become advantageous during field rolling operations to change the diameter of the tamping foot, the moisture content of the soil would not have to be adjusted accordingly.

Of equal importance is the fact that the greatest effect, or variation in dry density, of foot diameter occurred at a water content equal to the optimum moisture. Since this is the moisture content almost invariably striven for in field compaction operations, it is of extreme interest to know that this is the very condition at which the dry density is most susceptible to variations in the diameter of the tamping foot.

The two inch foot, which transmitted the maximum pressure to the soil, produced the smallest densities, particularly when compaction was performed at moisture contents less than the optimum moisture. Peak densities were obtained with the three inch foot; density values diminished when the foot size was increased. This behavior seems to substantiate previously described theories regarding the effect of bearing capacity with relation to stress intensity on the face of the tamping foot. During the tests the small foot completely disturbed the soil by punching deep and fast and displacing a large volume of soil in an outward direction. This displacement gradually decreased as the density increased until finally excellent compaction appeared to be achieved with the small foot. Since with a cohesionless material bearing capacity varies with the size of the loaded area, the fact that the two inch diameter foot sheared the soil excessively when at moisture contents less than optimum is a logical phenomenon as in the drier ranges this soil approached the cohesionless condition. Sowers and Gulliver, in a paper published by the Highway Research Board, indicated that the probable cause of the decrease in density with continued increase in foot size is the rigidity of the tamping foot.(29) They explain that the wider the foot, the greater are the irregularities in the density and thickness of the layer being compacted; therefore the foot tends to ride on the high hard spots and leave the remainder uncompacted.

Another interesting observation from Figure 7 is the similarity of the laboratory curve produced by the three inch diameter foot and the Marshall hammer to that produced by the standard Proctor test with separate soil portions. The only explanation plausible seems to be in the effect of the size of the compaction mold with respect to the size of the compaction foot. No attempt was made to further investigate this effect during this study. Compacted samples are shown along with their respective molds and hammers on the following page.

Fig. 11
ONE-SIXTH CUBIC FOOT AND ONE-THIRTIETH CUBIC FOOT COMPACTED SAMPLES WITH THEIR RESPECTIVE COMPACTION MOLDS AND HAMMERS

From the data contained in the moisture-density curves, plots of dry density versus foot diameter were made for conditions of equal moisture content. (See Figure 8). The results show that the effect of foot size is much more pronounced at lower values of moisture content than at the higher values; when the moisture content approached saturation conditions, as represented by a water content of twenty-seven per cent, foot size had no effect whatever on the density obtained. A test series was conducted at approximately twenty per cent moisture content using a compactive effort fifty per cent greater than that used previously. The water content was selected to approximate the optimum moisture content at this particular compactive effort. With a noticeable exception, the curve obtained exhibits an almost identical shape to and pronounced peak like the low effort curve at optimum moisture. The foot size which produces the maximum compaction appears to decrease as the compactive effort increases. The two inch diameter foot, as previously suspected, performed much better with the larger compactive effort, i.e. with increased blows per layer.

In field rolling, the spacing of the feet has a bearing on contact pressures and per cent coverage. Per cent coverage is expressed as the actual area of tamping feet in contact with the ground in one pass divided by the area passed. The Highway Research Board contends that, other things being equal, the greater the tamping foot area, the fewer passes are required to compact the soil.(30) They also found that the relationship between density and number of passes is approximately a straight line when plotted on semilogarithmic paper, as is the relationship found in the laboratory between number of blows and density obtained in the laboratory compaction test.

In order to investigate these theories in the light of the data found in this investigation, a dry density versus per cent coverage relationship was plotted. (See Figure 9). For laboratory dynamic compaction tests, per cent coverage was expressed as the product of the area of the compaction foot and the number of blows per layer divided by the area of the compaction mold. Dry density was plotted as a linear ordinate while per cent coverage was plotted as the abscissa on a logarithmic scale. Straight line curves exhibited, as would be expected, shapes similar to those shown on Figure 8; however, the degree to which points calculated from the standard Proctor curve approached these curves is worthy of note and further investigation. A curve was also plotted for the 18,630 foot-pounds per cubic foot tests at its optimum moisture content; the curve closely resembles that of the 12,420 foot-pounds per cubic foot test. The peak for both curves was obtained at four hundred per cent coverage; this coverage represents a foot size of three inch diameter with the smaller effort and approximately a two and one-half inch foot size for the larger effort. These results indicate that the foot size best suited for compacting a particular soil is a function of the compactive effort and decreases as the effort increases.

On Figure 10 is a plot of dry density versus blows per layer at a water content of twenty per cent. On this same figure data obtained from the previously mentioned Highway Research Board publication is presented for comparison.(31) The similarity of the slope of the lines is striking as is the marked improvement of the two inch diameter foot with increased blows. For field operations requiring high degrees of density, it would appear that the most efficient method of achieving these density requirements would be to decrease the size of the tamping foot at various stages of the rolling operations. Thus as the density increased, along with the soil's bearing capacity, smaller tamping feet transmitting higher pressure intensities could be substituted for the initially larger feet. Even if the degree of rolling necessary to obtain the required compaction is insufficient to economically permit changing feet during the rolling, considerable efficiency could result from proper selection of the foot size to use throughout the operation. In view of the previously mentioned similarities between field and laboratory tests, it is believed that correlation between field equipment and laboratory tests can be achieved to permit this selection.

CHAPTER VI

CONCLUSIONS

The following conclusions have been derived from this research:

1. The density obtained from dynamic compaction is dependent upon the area, or diameter, of the compacting foot.
2. For a given soil, moisture content, and method of dynamic compaction, there is a particular foot diameter which will produce the most efficient compaction, i.e. achieve the greatest value of dry density with the same expenditure of compactive effort.
3. The effect on dry density of the size of the compacting foot is largest when the moisture content is near the optimum. At high values of moisture content which approach a saturated condition, the size of the compacting foot has little or no effect on density.
4. The optimum moisture content produced by dynamic compaction at like amounts of work is not related to the area of the compacting foot.
5. The optimum foot diameter appears to decrease as the compactive effort increases. The most efficient compaction

operation would be one in which the foot diameter was reduced at successive stages of the compaction process.

CHAPTER VII

RECOMMENDATIONS

Though this investigation was admittedly limited, nevertheless the results definitely suggest that the efficiency of the compaction process can be improved upon. Several suggestions for further investigation concerning the efficiency of laboratory and field compaction are warranted from the results.

The laboratory test equipment used during this study, i.e. the one-sixth cubic foot mold and the Marshall type hammer, are well suited for compaction research and study of variables affecting dynamic compaction. Extensive investigation with this equipment aimed at establishing a definite relationship between optimum foot diameter and compactive effort is a primary recommendation. In conjunction with such tests, it is highly recommended that the laboratory relationship between dry density and per cent coverage be carefully considered as an aid in the investigation.

Before research of this nature can be practically applied, the effect on various soils must be determined. Investigations such as the one presented in this report must be performed on all types of soils before a complete compaction efficiency study can be achieved.

The shape of the compaction foot is a factor influencing soil density.(32) In this study only circular plates were investigated. This variable presents a challenging research project of unusual scope.

For experimental research purposes the laboratory equipment used proved satisfactory; however, for practical laboratory soil testing, a much smaller compaction device requiring considerably smaller samples would be helpful. Indications from the comparisons made with the standard Proctor mold and hammer are that correlation of results between different laboratory equipment is possible. The key to this correlation appears to be in the confining effects of the mold; a relationship between mold diameter and optimum foot diameter may well exist.

Once a thorough understanding of the effect of the compacting foot on the efficiency of laboratory compaction has been attained, study should then be turned toward the development of practical correlation between field and laboratory compaction equipment. It is recognized that such a correlation study would be tremendous in scope, but from the similarity of trends established in this investigation to predictions based on observations of field rolling behavior and soil bearing capacity theories, there appears to be every indication that such a correlation could be successfully achieved. With competition keen and equipment prices spiraling, a contractor with versatile equipment that can be modified readily to operate at maximum efficiency with varying soil and density requirements would be in an enviable position indeed.

APPENDIX

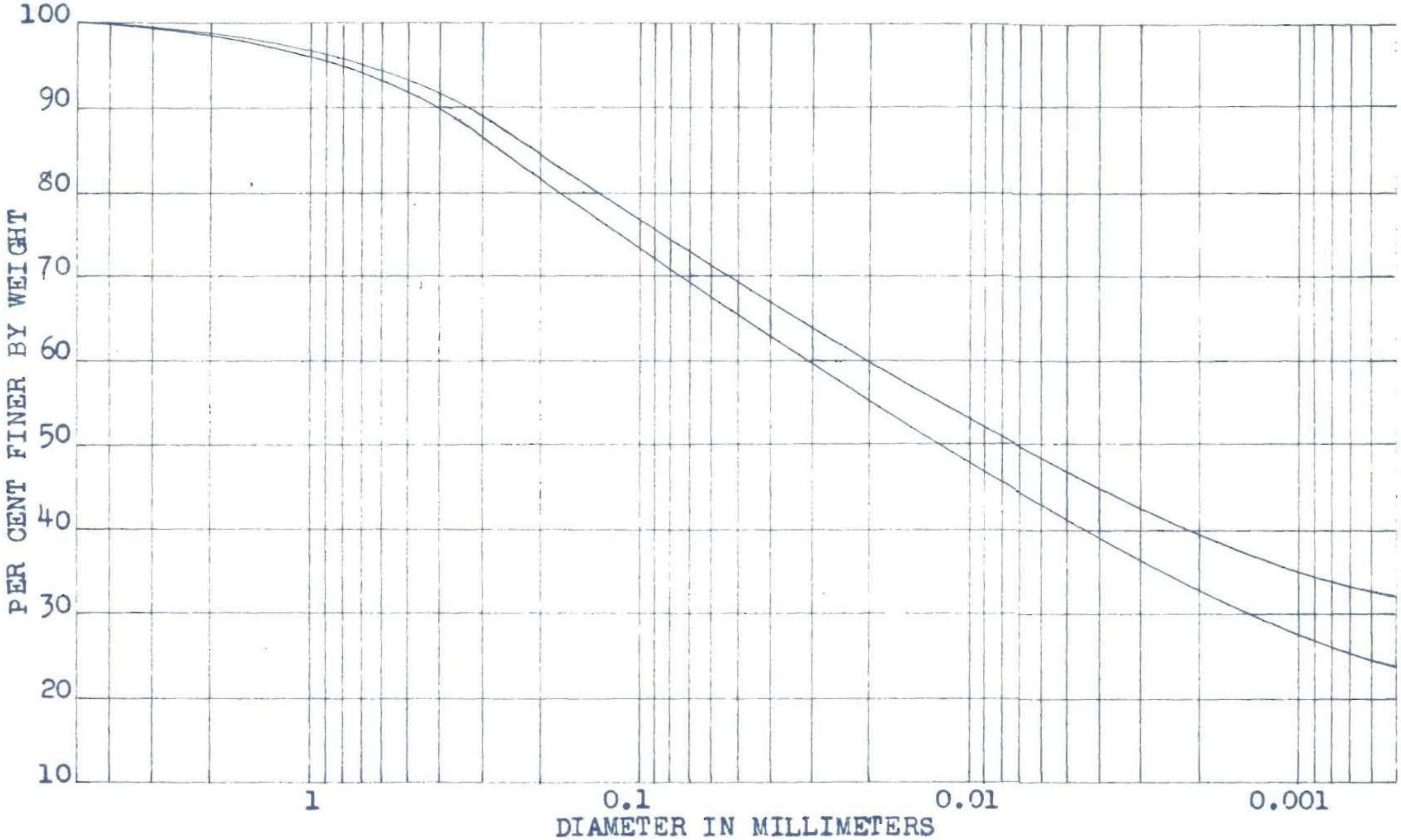


Fig. 12
GRAIN SIZE DISTRIBUTION OF TEST SOIL

COMPACTION TEST DATA SHEET: Sample No. 5/24-1

foot size 5", water content 24%

Water Requirements:

	batch weight W	initial W.C. W_i 7/25/58	weight soil W_s $(W/1+w_i)$	weight water avail. W_{AV} $(W-W_s)$	water required % w	weight total W_R (wW_s)	weight addi. W_{AD} (W_R-W_{AV})
can 1	7	15.78	6.05				
can 2	7	10.67	6.33				
can 3	7	10.49	6.34				(1009)
total	21		18.72	2.28	24	4.50	2.22

Water Contents:	after prep.	after stab.	after compaction		
date	7/26	7/28	7/28	7/28	
time	1545	1525	1625	1630	
container no.	16	16	17	18	
wt. wet soil+can	88.189	85.000	96.477	93.451	
wt. dry soil+can	75.522	73.022	82.340	79.857	
wt. water	12.667	11.978	14.137	13.594	
wt. container	21.297	21.297	20.881	20.821	
wt. dry soil	54.225	51.725	61.459	59.036	
water content	23.4	23.2	23.0	23.0	

average: 23.0%

Density:

wt. soil+mold	50-8
wt. mold	30-7
wt. soil in mold	20-1
wt. per cu. ft.	120.375

dry density: 97.9

Remarks: Sample appears undamaged. 1st. layer to 2" mark, down 3/4". 2nd. layer to 3" mark, down 3/4". 3rd. layer over 1", final height good. Compaction good on all of the three layers. No loose material left on layers. No sticking to foot. Well layered.

Fig. 13
SAMPLE DATA SHEET

Table 1
Data from Compaction Tests with Two Inch Diameter Foot, Marshall Hammer and One-Sixth Cubic Foot Mold

sample designation	compactive effort	water content	weight of soil in mold	wet density	dry density
	f-p/c.f.	%	lbs.&oz.	p.c.f.	p.c.f.
2/15-2	12,420	15.1	17-11	106.3	92.3
2/18-2	12,420	17.5	18-11	112.3	95.5
2/21-3	12,420	19.9	19-4	115.5	96.4
2/21-2	12,420	20.4	19-11	118.3	98.1
2/24-2	12,420	23.0	20-0	120.0	97.5
2/27-1	12,420	25.7	20-3	121.1	96.5
2/27-2	12,420	25.8	20-2	120.8	96.0
SP/21-1	18,630	19.7	20-4	121.5	101.5

Table 2
Data from Compaction Tests with Three Inch Diameter Foot, Marshall Hammer and One-Sixth Cubic Foot Mold

sample designation	compactive effort	water content	weight of soil in mold	wet density	dry density
	f-p/c.f.	%	lbs.&oz.	p.c.f.	p.c.f.
3/15-1	12,420	14.7	18-7	110.6	96.5
3/15-2	12,420	15.4	18-6	110.3	95.5
3/18-3	12,420	16.4	18-12	112.5	96.6
3/18-2	12,420	17.3	18-15	113.8	97.0
3/21-3	12,420	19.4	19-9	117.6	98.5
3/21-2	12,420	20.7	20-0	120.0	99.5
3/24-2	12,420	22.4	20-5	121.9	99.5
3/24-1	12,420	23.1	20-5	121.9	98.8
3/27-1	12,420	25.8	20-3	121.1	96.4
SP/21-2	18,630	19.8	20-7	122.4	102.1

Table 3
Data from Compaction Tests with Four Inch Diameter Foot, Marshall Hammer and One-Sixth Cubic Foot Mold

sample designation	compactive effort	water content	weight of soil in mold	wet density	dry density
	f-p/c.f.	%	lbs.&oz.	p.c.f.	p.c.f.
4/15-1	12,420	14.9	18-5	109.9	95.6
4/18-1	12,420	17.9	19-2	114.8	97.4
4/18-2	12,420	17.9	19-1	114.4	97.0
4/21-3	12,420	21.1	19-13	118.9	98.0
4/21-1	12,420	21.4	19-13	118.9	97.8
4/24-1	12,420	23.1	20-6	122.3	99.3
4/24-2	12,420	23.3	20-3	121.1	98.2
4/24-3	12,420	23.9	20-4	121.5	98.1
4/27-1	12,420	25.9	20-3	121.1	96.4
4/27-2	12,420	25.9	20-4	121.5	96.5
SP/21-3	18,630	19.9	20-4	121.5	101.3

Table 4
Data from Compaction Tests with Five Inch Diameter Foot, Marshall Hammer and One-Sixth Cubic Foot Mold

sample designation	compactive effort	water content	weight of soil in mold	wet density	dry density
	f-p/c.f.	%	lbs.&oz.	p.c.f.	p.c.f.
5/15-1	12,420	15.0	18-3	109.1	94.9
5/18-1	12,420	17.6	19-0	114.0	97.0
5/21-2	12,420	20.6	19-10	117.8	97.5
5/21-1	12,420	21.4	19-14	119.3	98.1
5/24-1	12,420	23.0	20-1	120.4	97.9
5/27-1	12,420	26.2	20-3	121.1	96.0
SP/21-4	18,630	20.1	20-3	120.9	100.7

Table 5
Data from Standard Proctor Compaction
Tests with Separate Samples for Each Point

sample designation	compactive effort	water content	weight of soil in mold	wet density	dry density
	f-p/c.f.	%	lbs.&oz.	p.c.f.	p.c.f.
PR/15-1	12,375	14.1	3-11	107.8	94.1
PR/15-2	12,375	14.2	3-9	107.2	93.8
PR/18-2	12,375	16.9	3-14	113.1	96.8
PR/18-1	12,375	17.1	3-12	113.1	96.5
PR/21-1	12,375	19.9	3-15	118.8	99.0
PR/21-2	12,375	19.9	4-1	118.8	99.0
PR/24-1	12,375	22.8	4-1	121.5	99.0
PR/24-2	12,375	23.0	4-3	122.4	99.5
PR/27-2	12,375	25.6	4-2	120.5	96.0
PR/27-1	12,375	25.9	4-1	121.5	96.5

Table 6
Data from Standard Proctor
Compaction Tests with Reused Samples

sample designation	compactive effort	water content	weight of soil in mold	wet density	dry density
	f-p/c.f.	%	lbs.&oz.	p.c.f.	p.c.f.
1	12,375	11.3	3-4	97.8	87.9
2	12,375	14.4	3-8	105.6	92.1
3	12,375	16.6	3-12	113.0	97.0
4	12,375	19.7	3-15	118.9	99.1
T-1	12,375	20.5	4-0	120.6	100.0
5	12,375	23.4	4-1	123.3	100.0
6	12,375	28.9	4-0	121.3	94.2

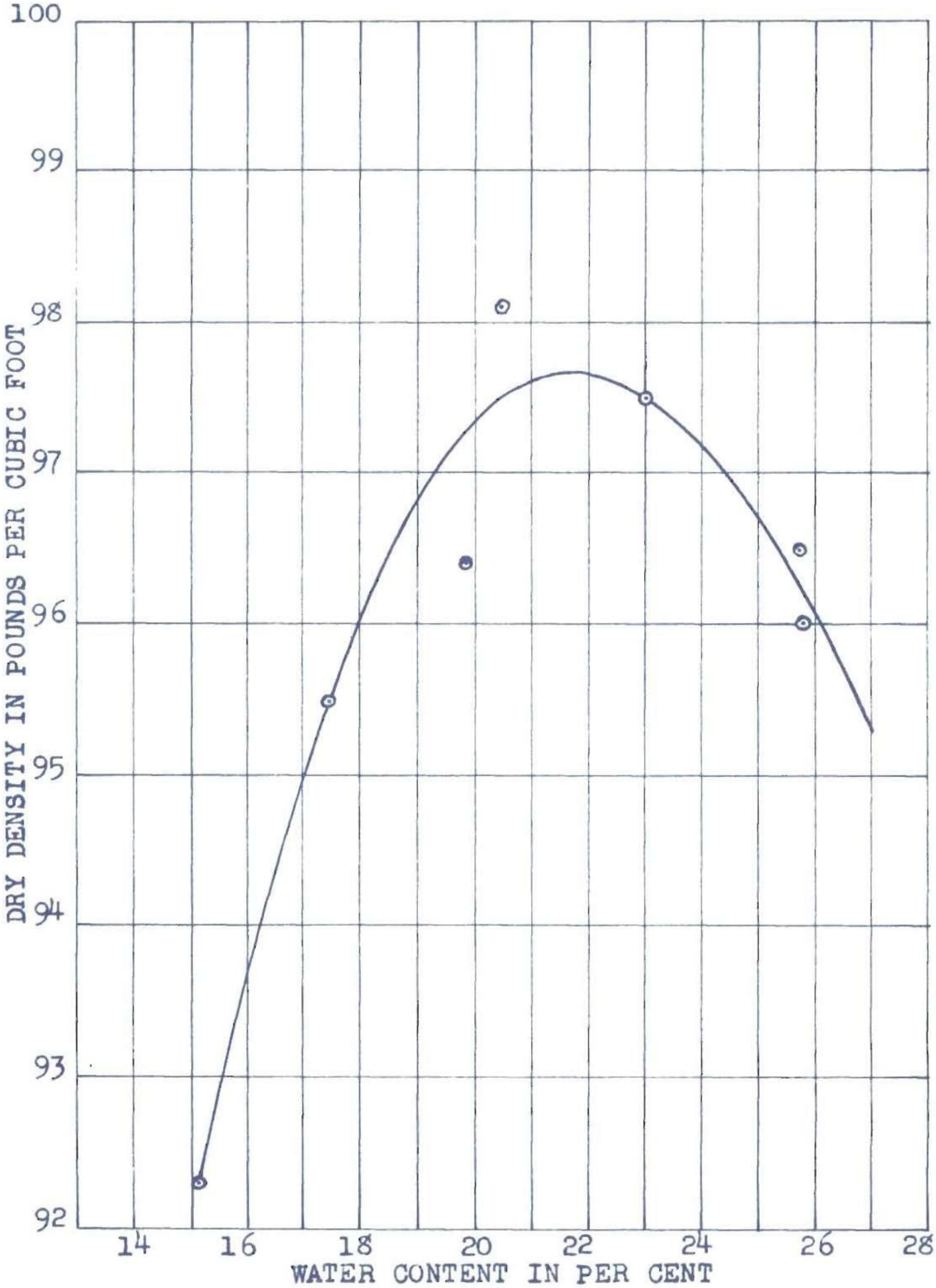


Fig. 14
MOISTURE-DENSITY CURVE FOR TWO INCH DIAMETER COMPACTION FOOT AT 12,420 FOOT-POUNDS PER CUBIC FOOT EFFORT IN ONE-SIXTH CUBIC FOOT MOLD WITH MARSHALL HAMMER

Fig. 15
MOISTURE-DENSITY CURVE FOR THREE INCH DIAMETER COMPACTION FOOT AT 12,420 FOOT-POUNDS PER CUBIC FOOT EFFORT IN ONE-SIXTH CUBIC FOOT MOLD WITH MARSHALL HAMMER

Fig. 16
MOISTURE-DENSITY CURVE FOR FOUR INCH DIAMETER COMPACTION FOOT AT 12,420 FOOT-POUNDS PER CUBIC FOOT EFFORT IN ONE-SIXTH CUBIC FOOT MOLD WITH MARSHALL HAMMER

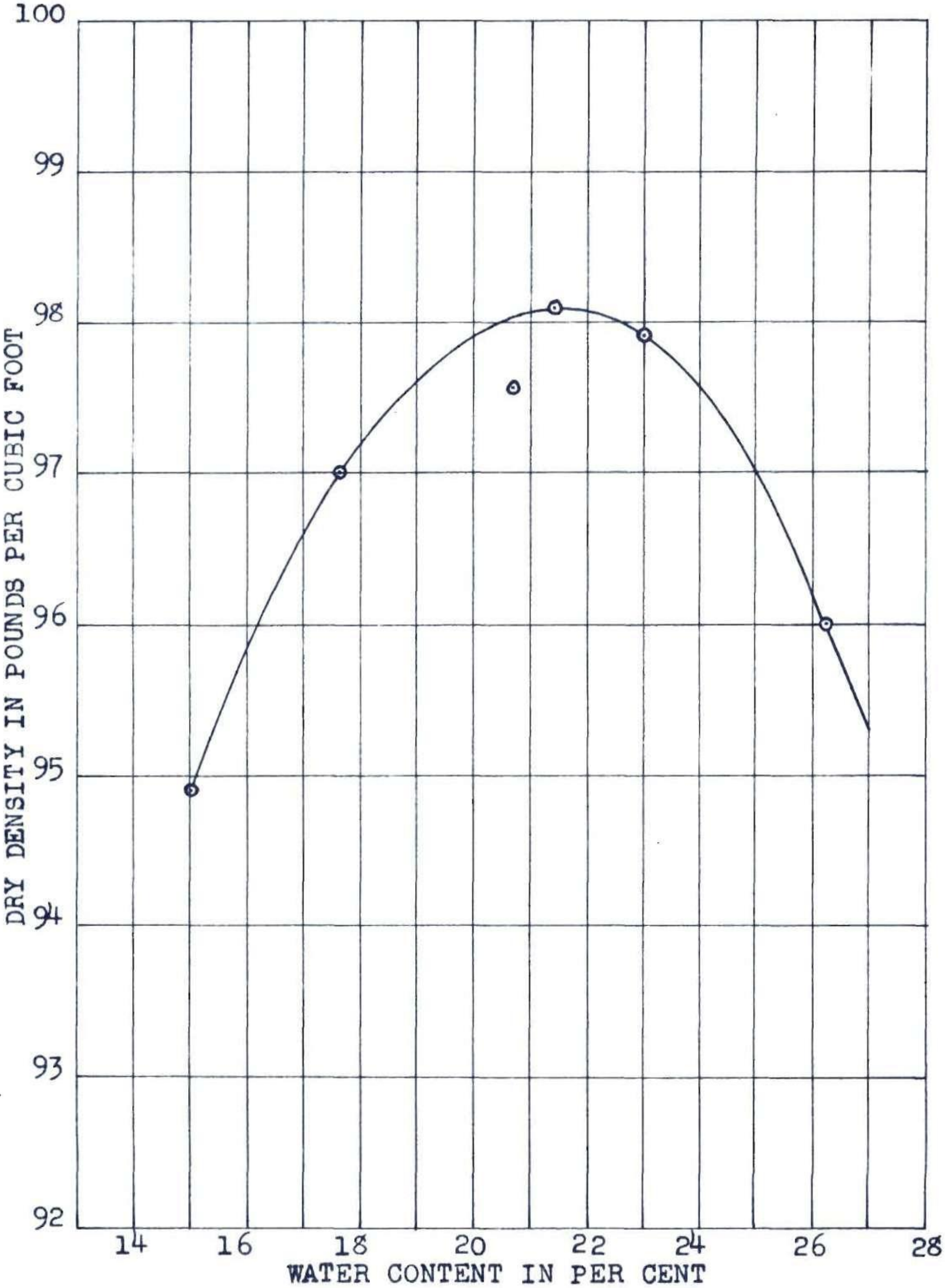


Fig. 17
MOISTURE-DENSITY CURVE FOR FIVE INCH DIAMETER COMPACTION FOOT AT 12,420 FOOT-POUNDS PER CUBIC FOOT EFFORT IN ONE-SIXTH CUBIC FOOT MOLD WITH MARSHALL HAMMER

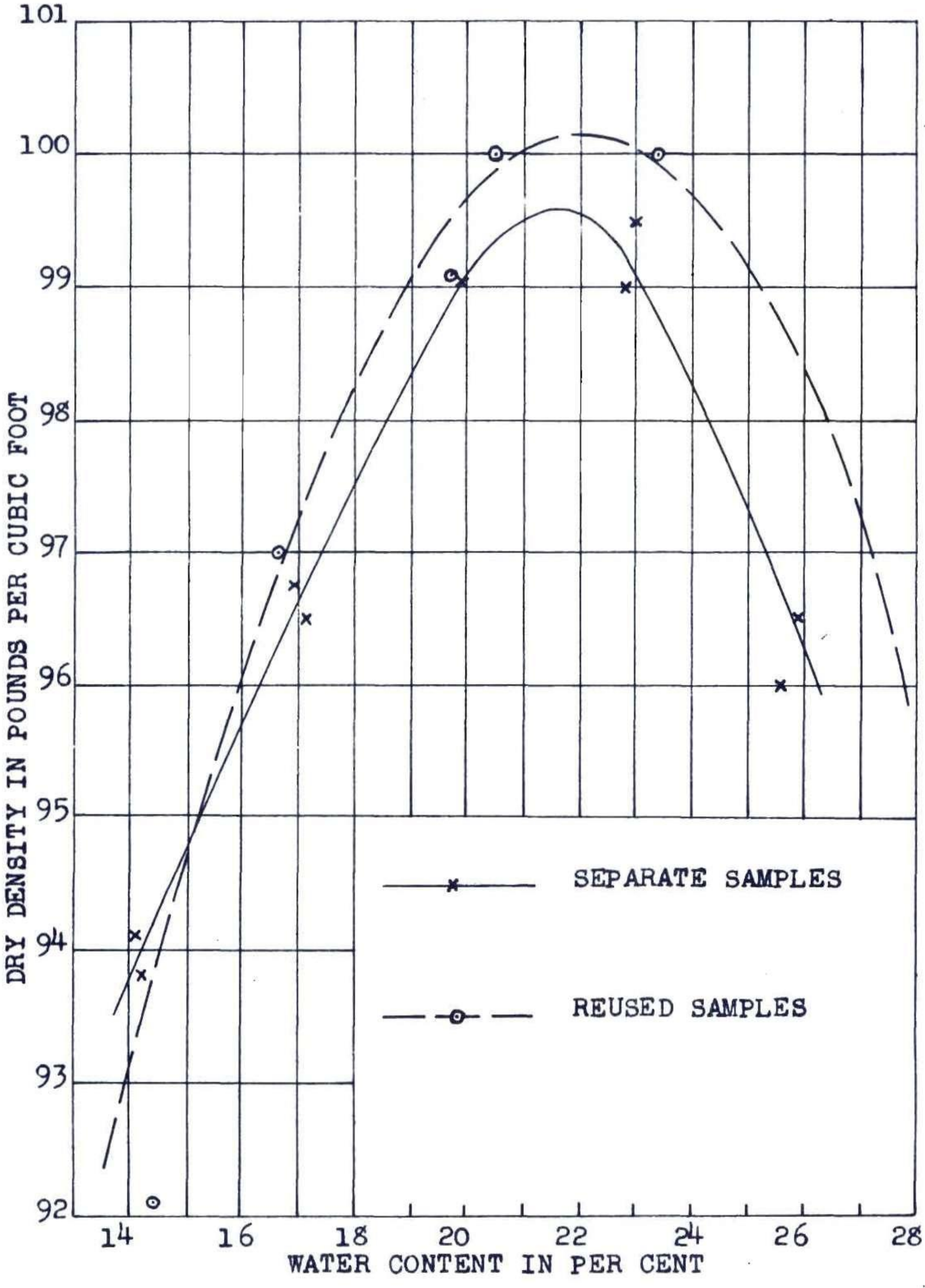


Fig. 18
MOISTURE-DENSITY CURVES FOR
STANDARD PROCTOR COMPACTION

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